Gas Density/Pressure Enhanced Regions as Favorable Places for the Formation of Planetesimals via Gravitational Instability

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Pressure-Enhanced Regions

Pressure/density structures can appear in a disk due to

1) the radial out-flow of gas molecules due to the inward radial migration of solids due to the gas drag

(Korbet et al. 2001)

2) the appearance of vortices

(Barge & Sommeria 1995, Bracco et al. 1998, Klahr & Bodenheimer 2003)

3) clumps

(Boss 2001, Mayer et al. 2004, Rice et al. 2004, Durisen et al. 2005)

4) interaction of the disk with a stellar companion

(Mayer et al. 2005, Boss 2006)

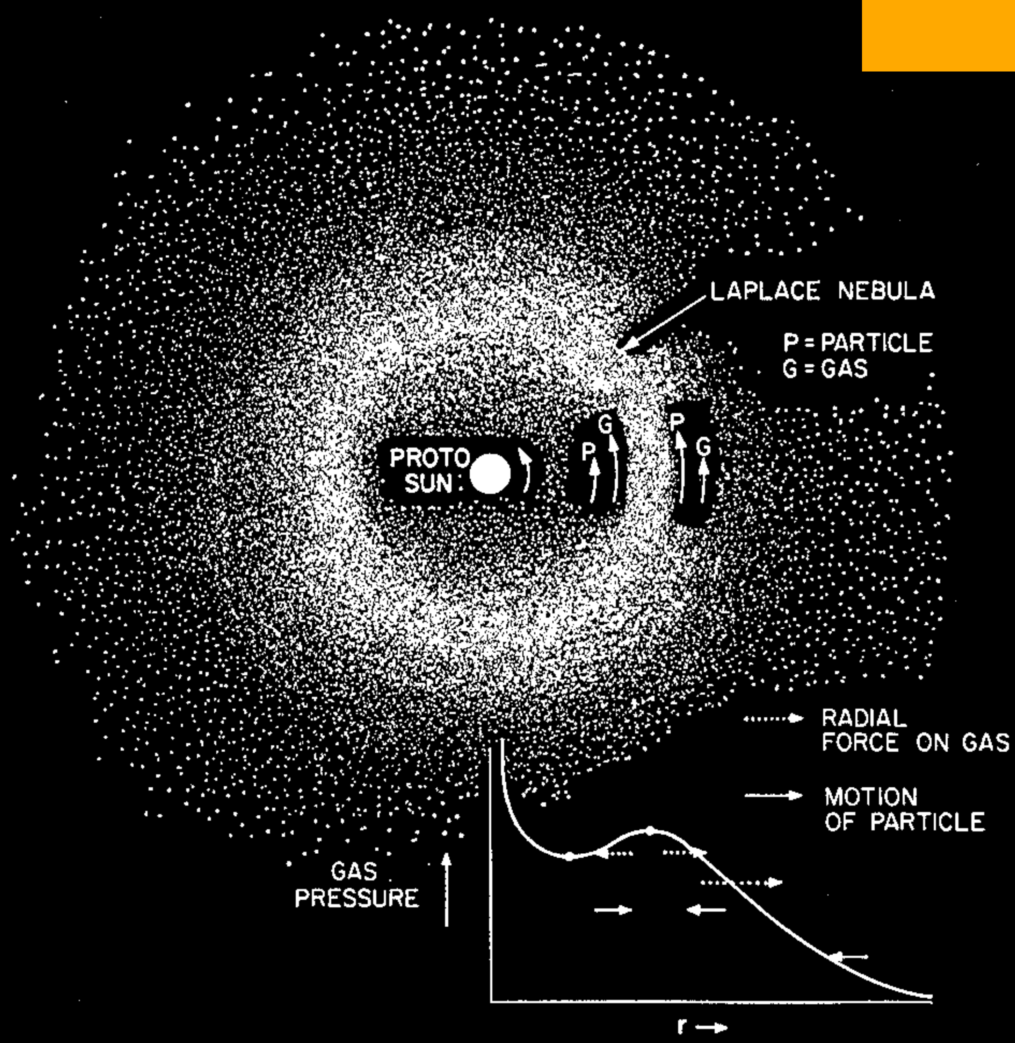
Gas Pressure

Gas angular frequency

$$r\omega_g^2 = r\omega_K^2 + \frac{1}{\rho_g(\vec{R})}\frac{\partial P_g(\vec{R})}{\partial r}$$

Keplerian frequency

Gas density



Objects outside the maximum pressure feel a headwind and spiral toward the star, whereas objects inside feel a tailwind and spiral out.

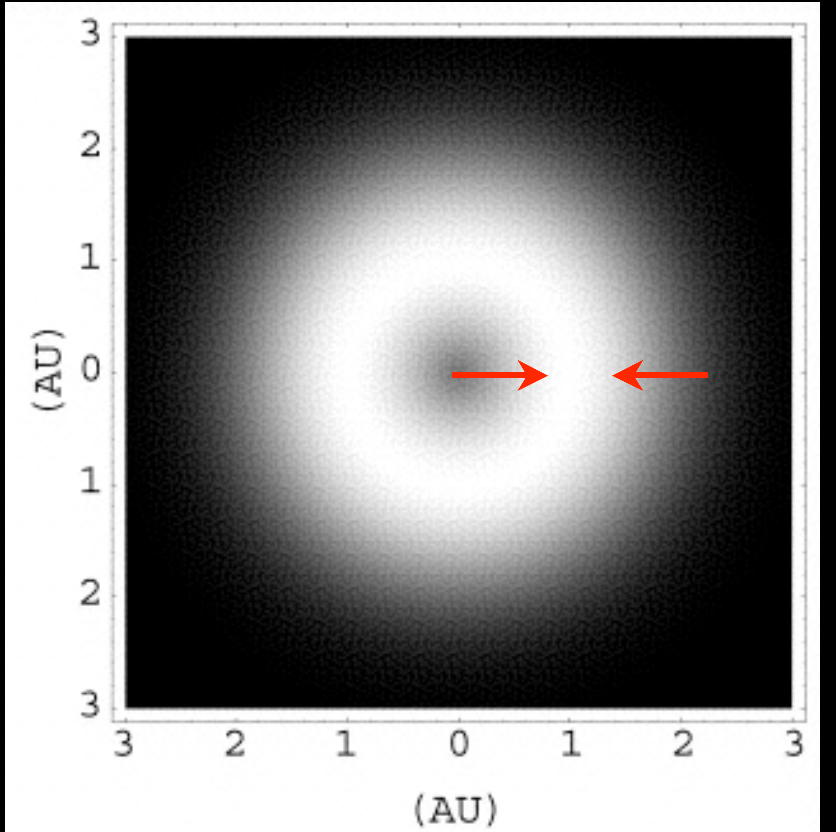
A Heuristic Model

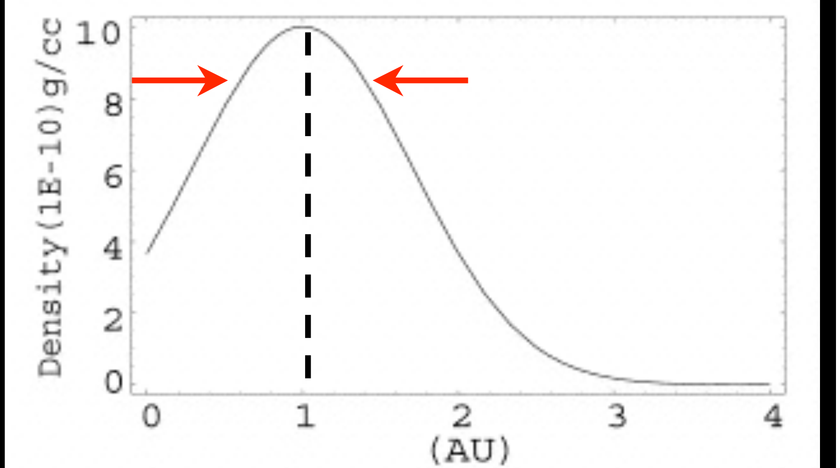
(Haghighipour & Boss 2003)

$$\rho_g(r,z) = \rho_g(r,0)\,\exp\left\{\frac{GMm_0}{K_B T}\left[\frac{1}{\left(r^2+z^2\right)^{1/2}} - \frac{1}{r}\right]\right\}$$

$$\rho_g(r,0) = \rho_0\,\exp\left[-\beta\left(\frac{r}{r_m}-1\right)^2\right]$$

Gas : Molecular Hydrogen
Star : Sun
T = 100 K
ρ_0 = 10^{-9} g/cm^3
β = 1
r_m = 1 AU

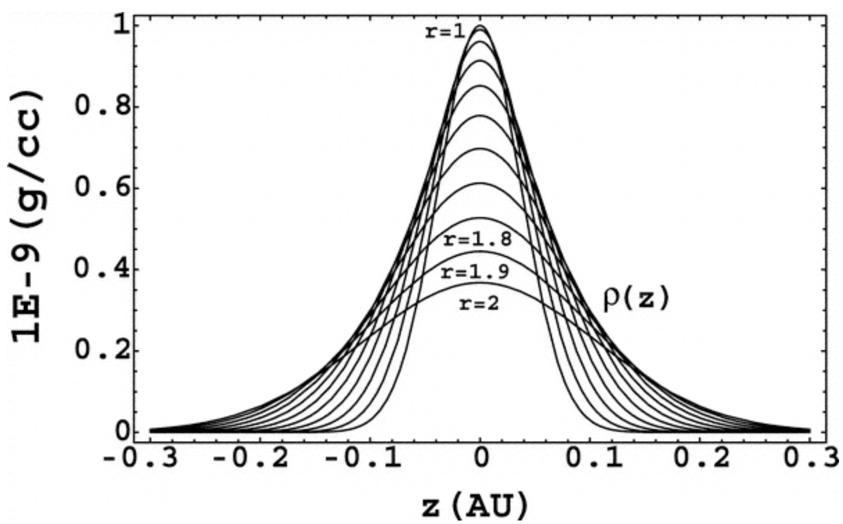


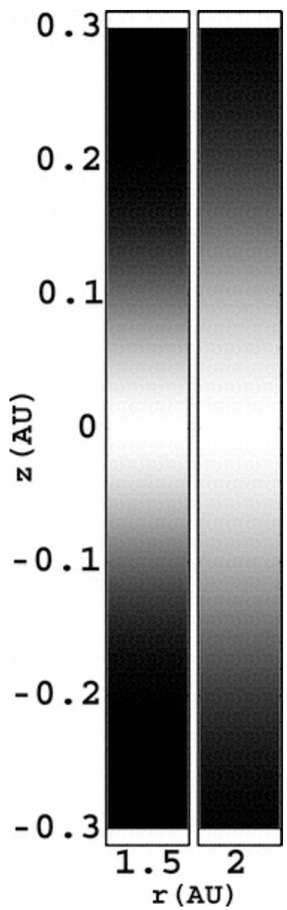


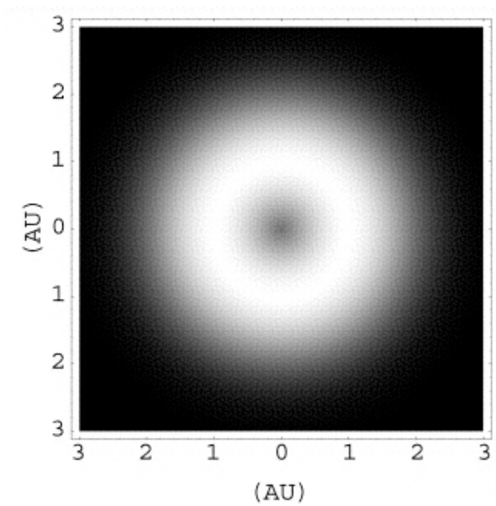
A Heuristic Model

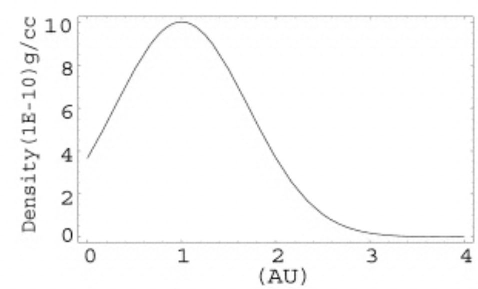
$$\rho_g(r,z) = \rho_0 \, \mathrm{Exp}\left\{ \frac{8GM}{\pi \, \bar{v}_{\mathrm{th}}} \left[\frac{1}{\left(r^2+z^2\right)^{1/2}} - \frac{1}{r} \right] - \beta \left(\frac{r}{r_m} - 1 \right)^2 \right\}$$

$$\rho_{\mathrm{dust}} = 0.0034 \;\rho_g$$



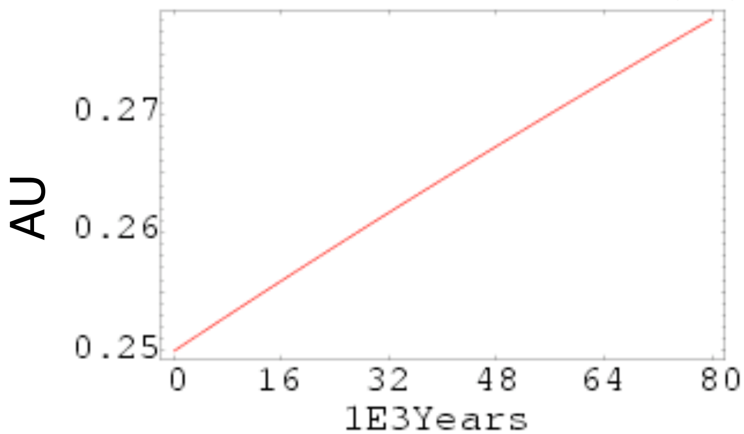


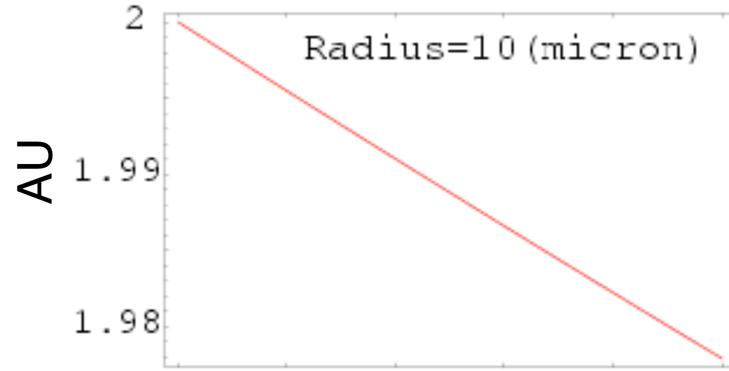




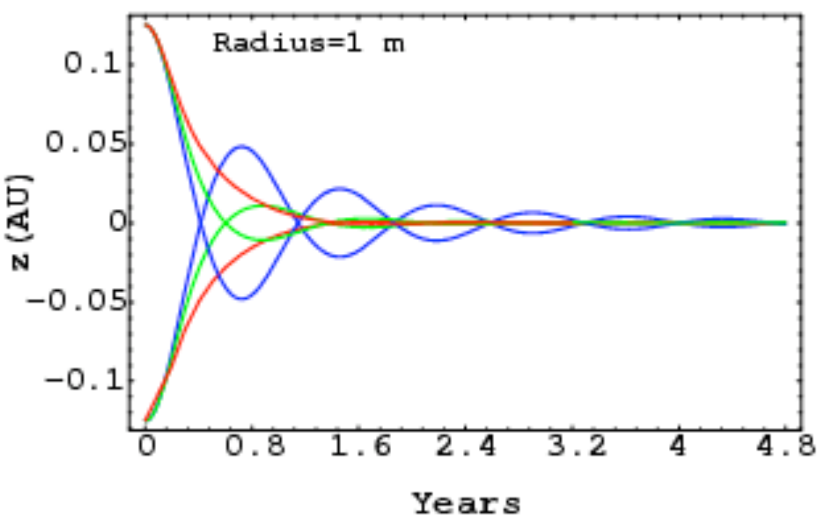
Radial migration of a dust particle

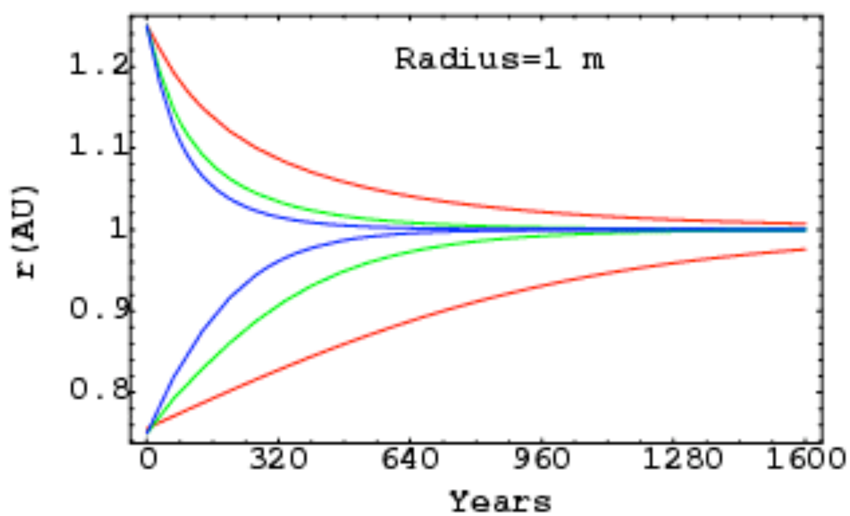
(Haghighipour & Boss, 2003a)





Vertical(left) and radial (right) migration of a meter-size object

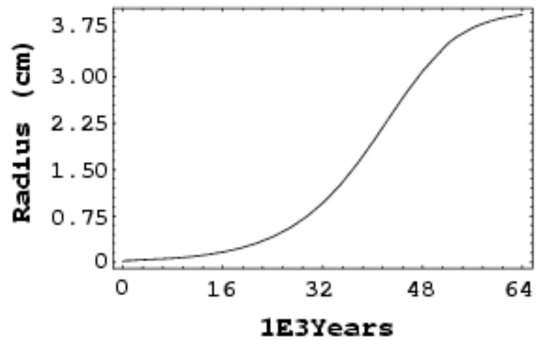


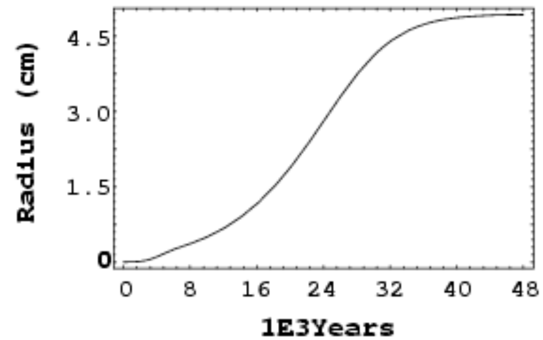


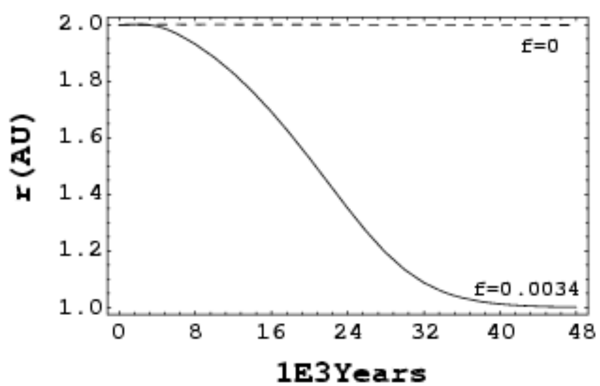
(Haghighipour & Boss, 2003b)

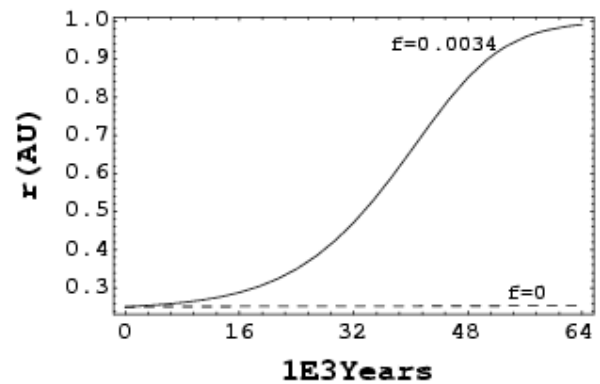
Growth and migration of a 10 micron-sized particle

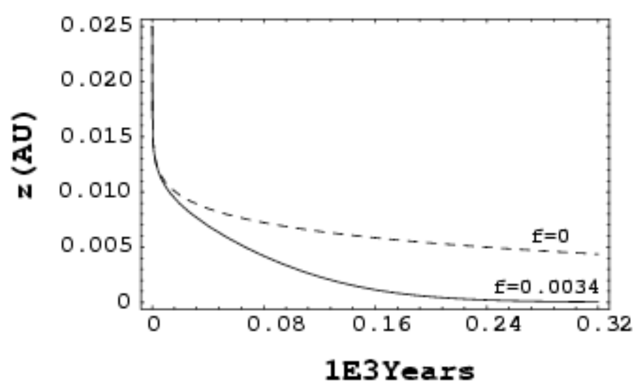
(Haghighipour, 2005)

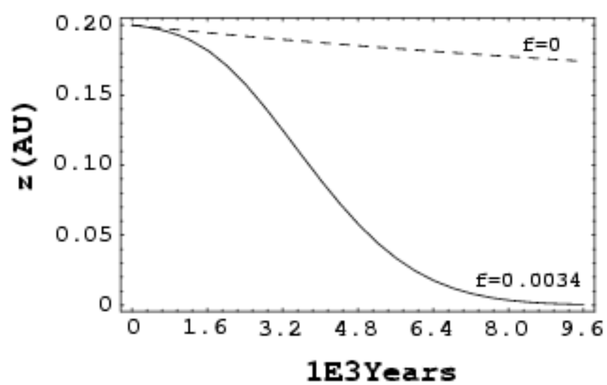










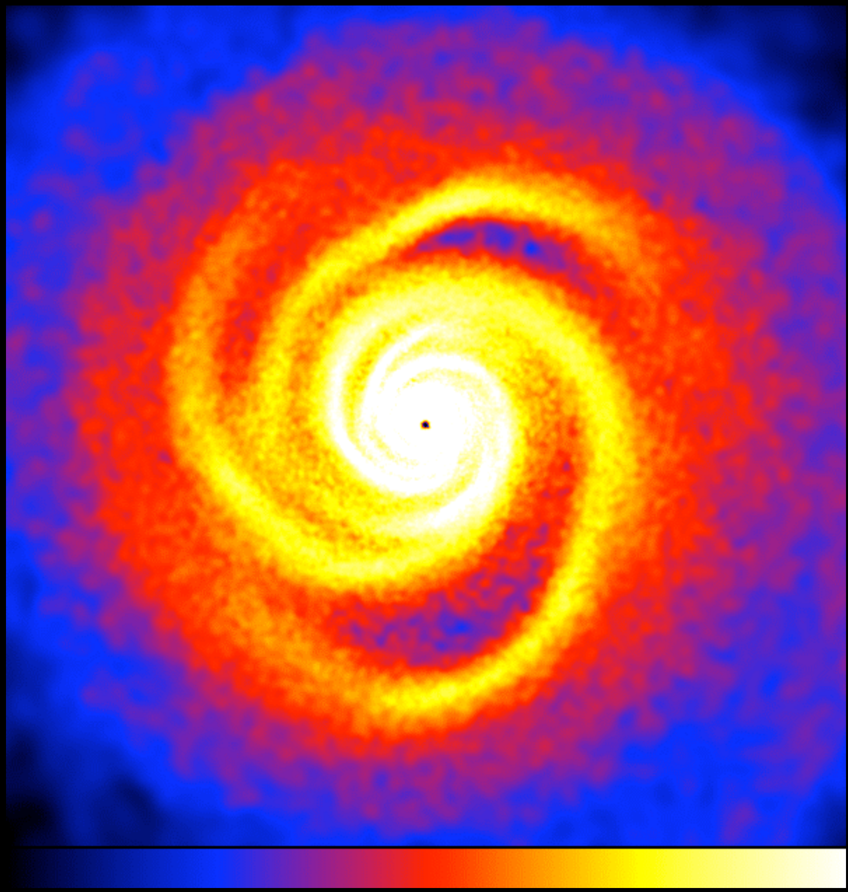


Self-gravitating discs

-Pressure gradient changes sign across spiral structures.

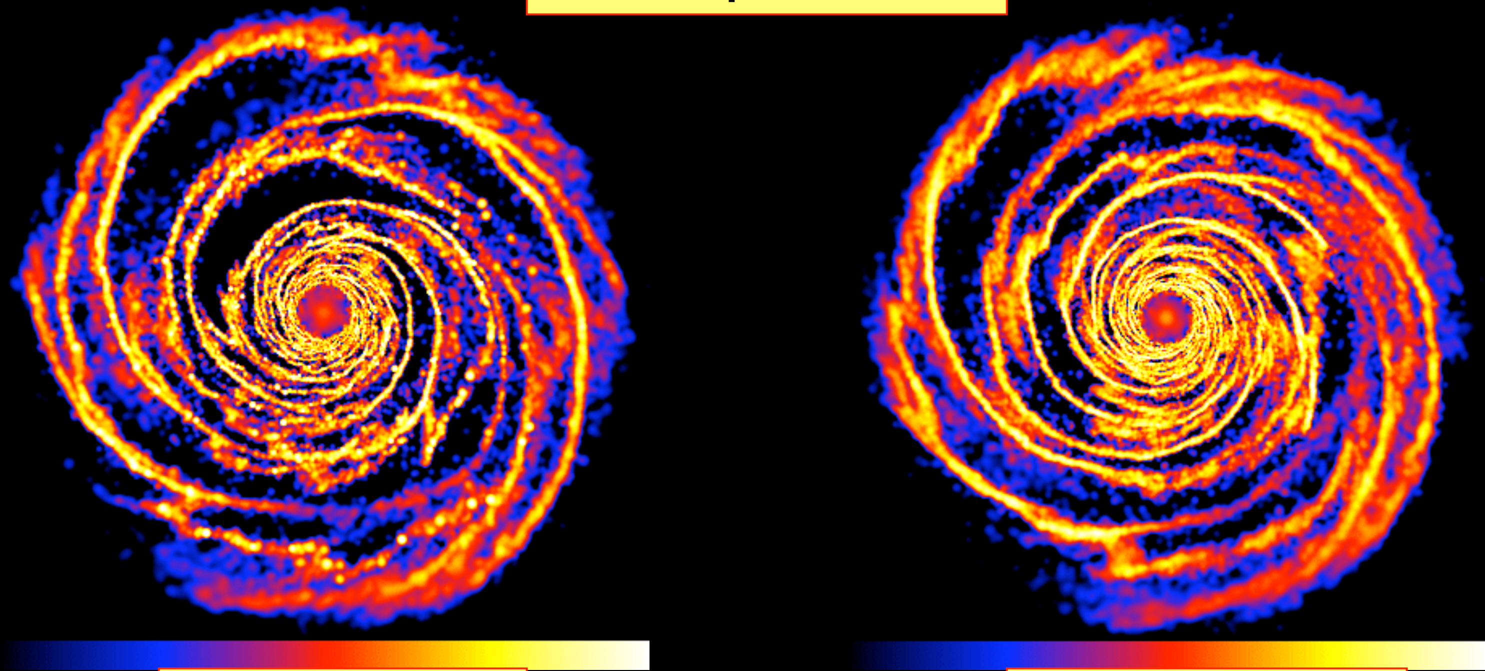
-Dust grains/small planetesimals can drift both inwards and outwards.

- Net effect - grains concentrate in the center of the spiral structures (Haghighipour & Boss 2003; Rice et al. 2004).



Direct planetesimal growth

150 cm particles



$M_{dust}/M_{gas} = 1/100$

$M_{dust}/M_{gas} = 1/1000$

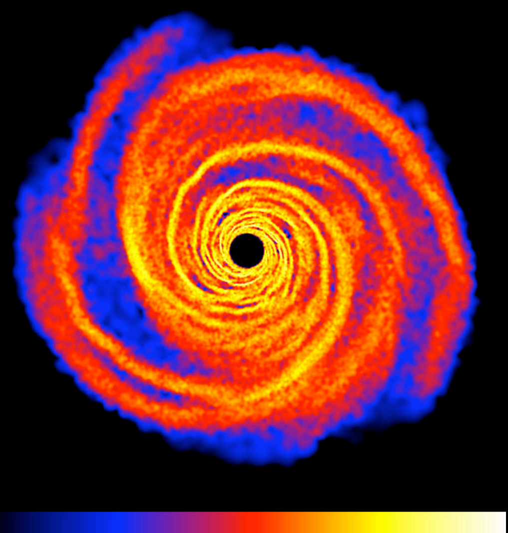
- Consistent with the metal-rich nature of planet host stars!

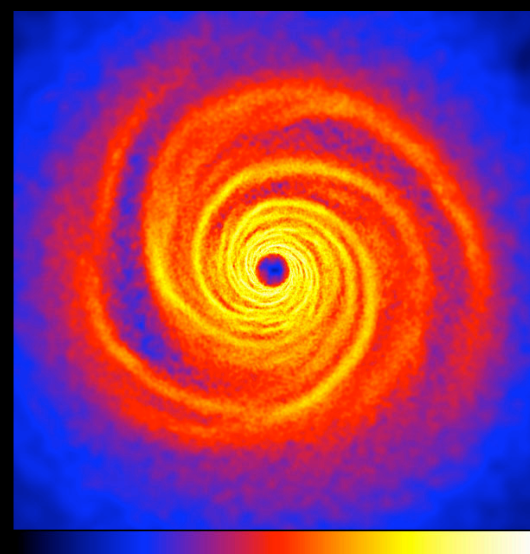
Dust evolution

- Large particles
  - decoupled from gas.
  - Structure largely matches that of the disc gas.

- Intermediate size particles
  - gas drag causes significant drift.
  - concentrate in the center of the spiral arms.

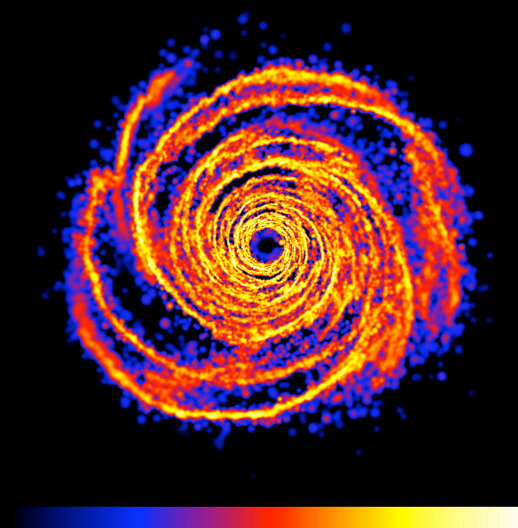
1000 cm





gas

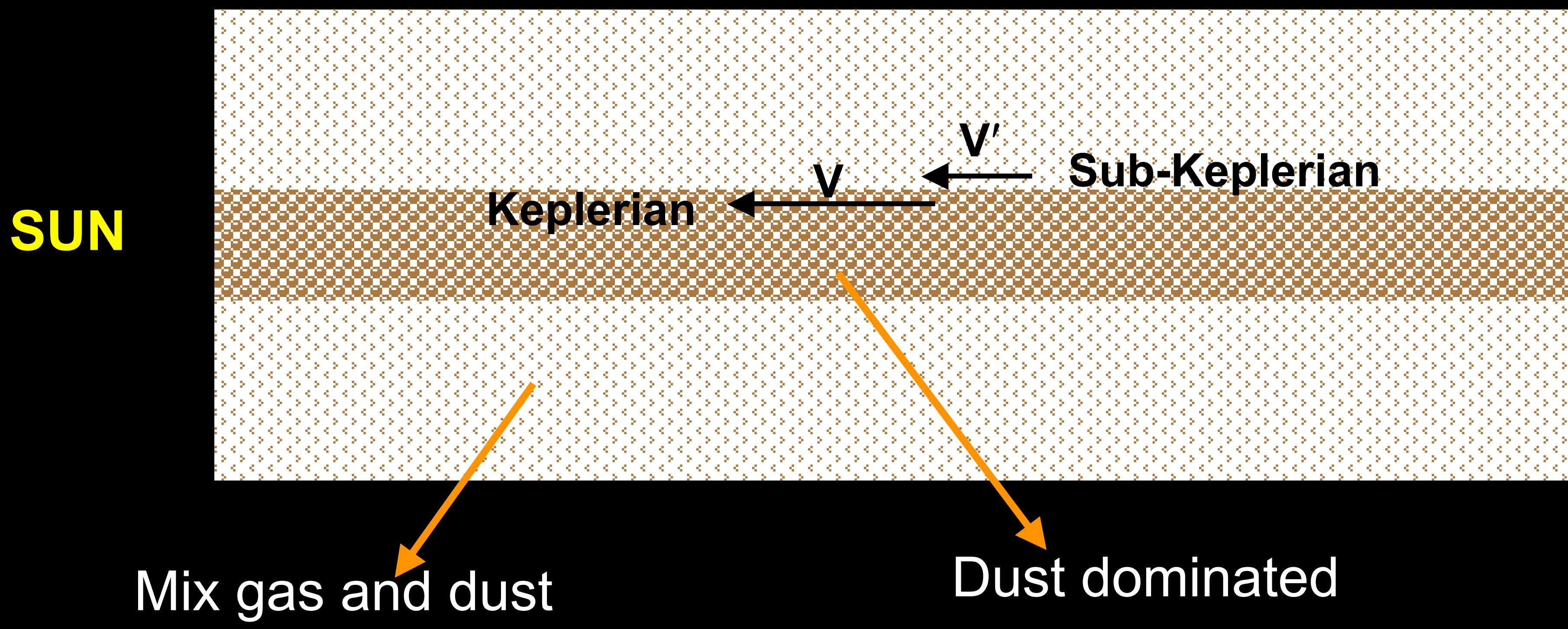
50 cm



(Rice et al. 2004).

Gravitational Instability

After a dust layer is formed around the midplane, the difference between gas and dust velocities produces Shear-induced turbulence



Are There Regions in a Nebula where Shear-Induced Turbulence may be Non-existance?

Shear-induced turbulence is caused because there is pressure-gradient.

$$\omega_g = \frac{GM}{\left(r^2 + z^2\right)} + \frac{1}{r\rho_g(r,z)} \frac{\partial P_g(r,z)}{\partial r}$$

Are there regions in a nebula where pressure gradient vanishes?

Nebula ~ Ideal gas

$$P_g = K_B T_g \rho_g / m_H$$

In a region where pressure gradient vanishes

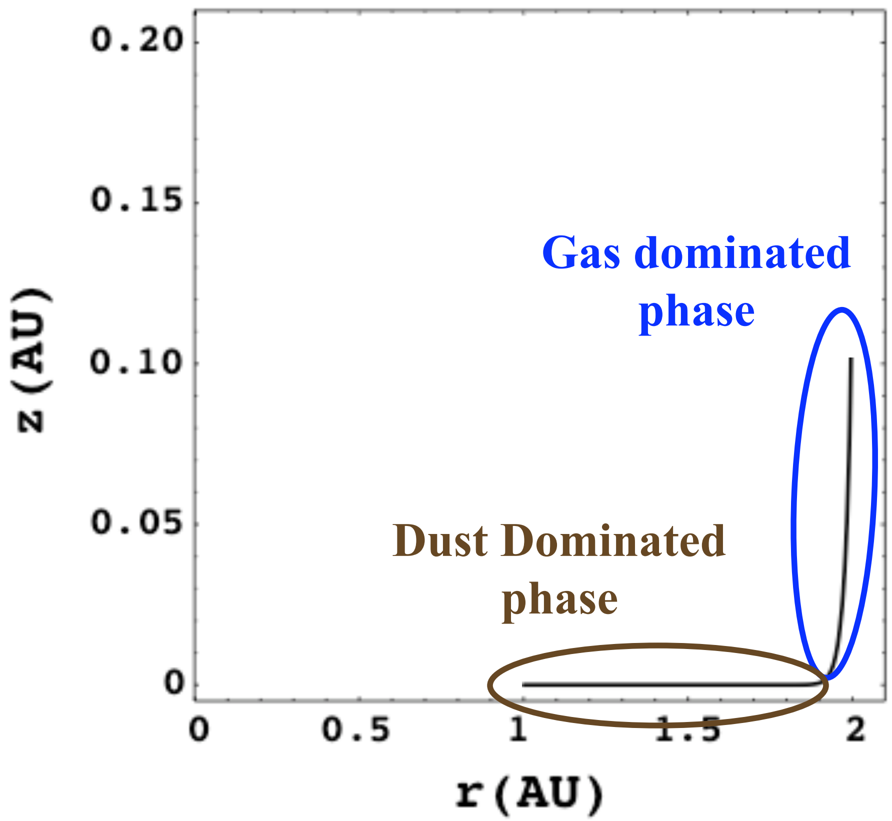
$$\frac{\partial P_g(r,z)}{\partial r} \propto \frac{\partial \rho_g(r,z)}{\partial r}$$

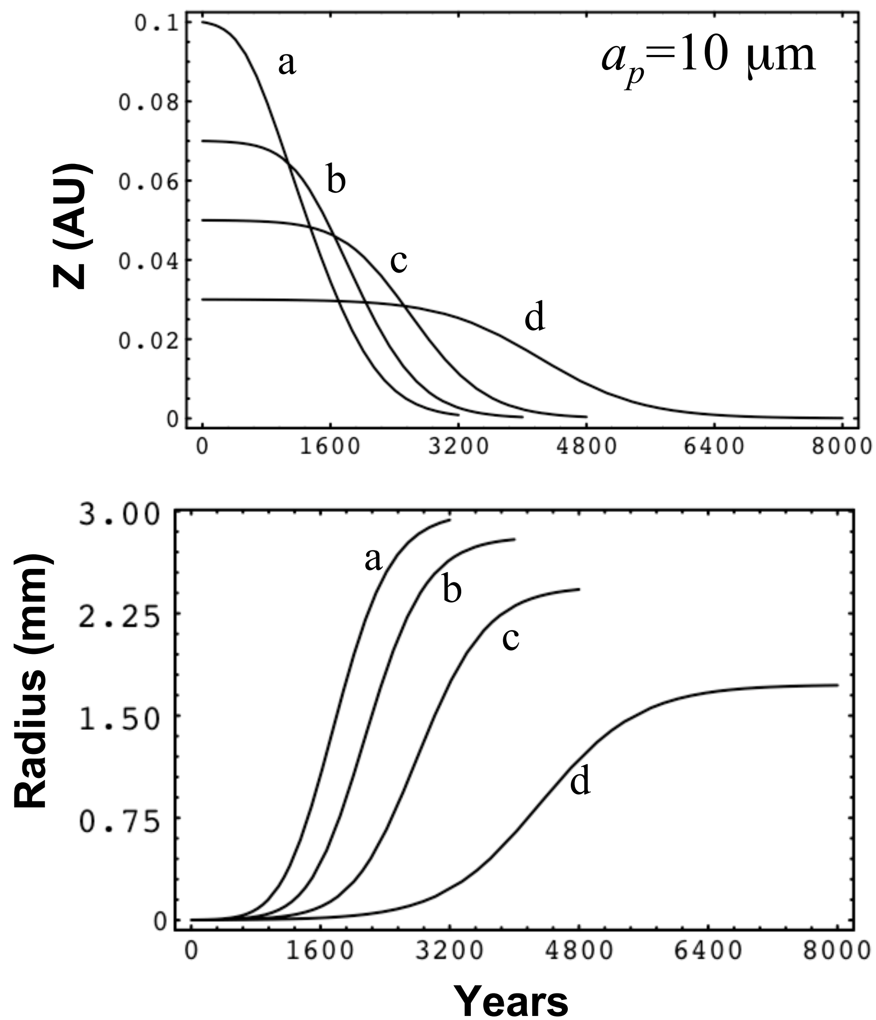
$$\frac{\partial \rho_g(r,z)}{\partial r} = 0$$

Regions where the density of the gas is maximum are shear-induced turbulence-free.

Vertical Settling and Particle Growth

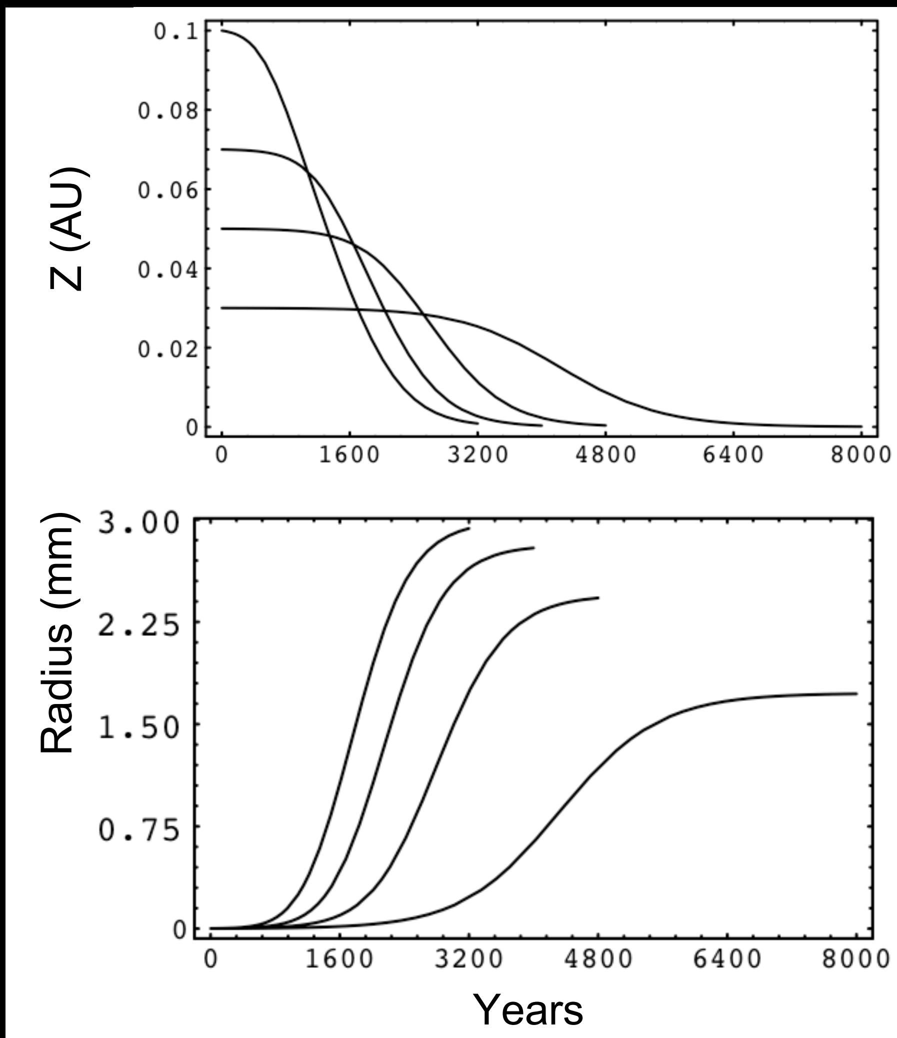
Dust particles grow to mm- and cm-size while settling on the midplane.

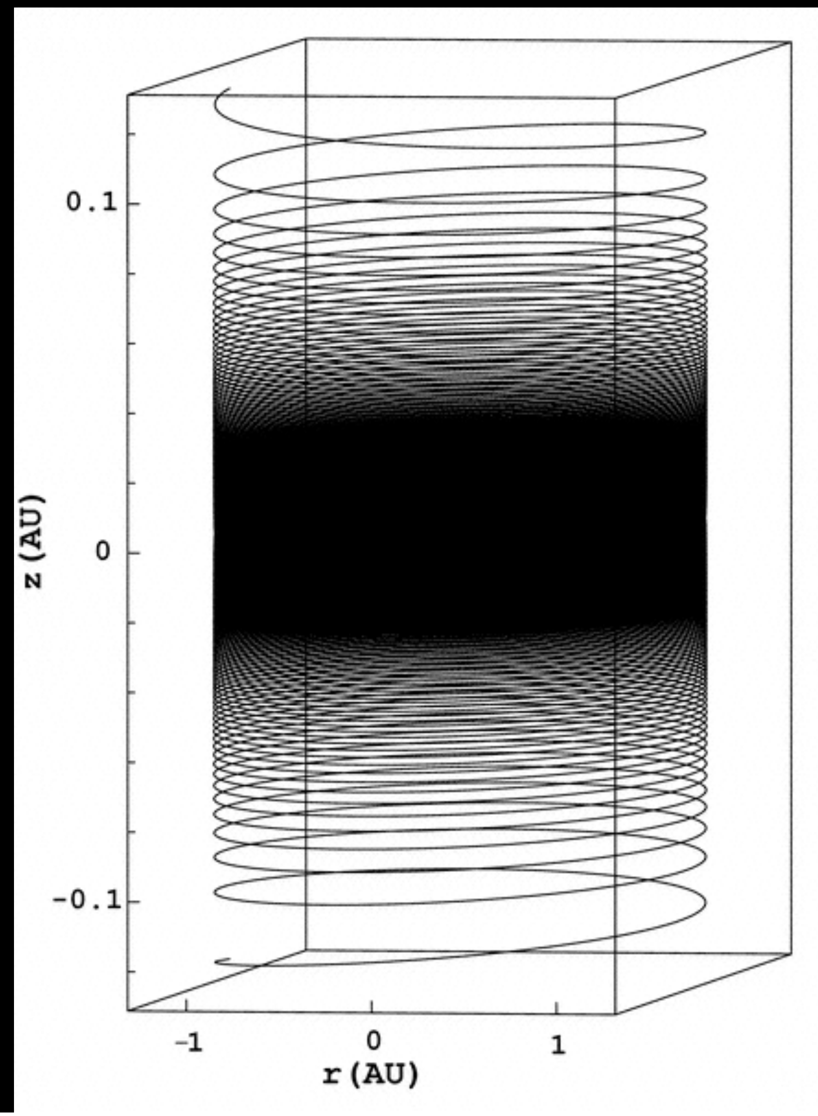




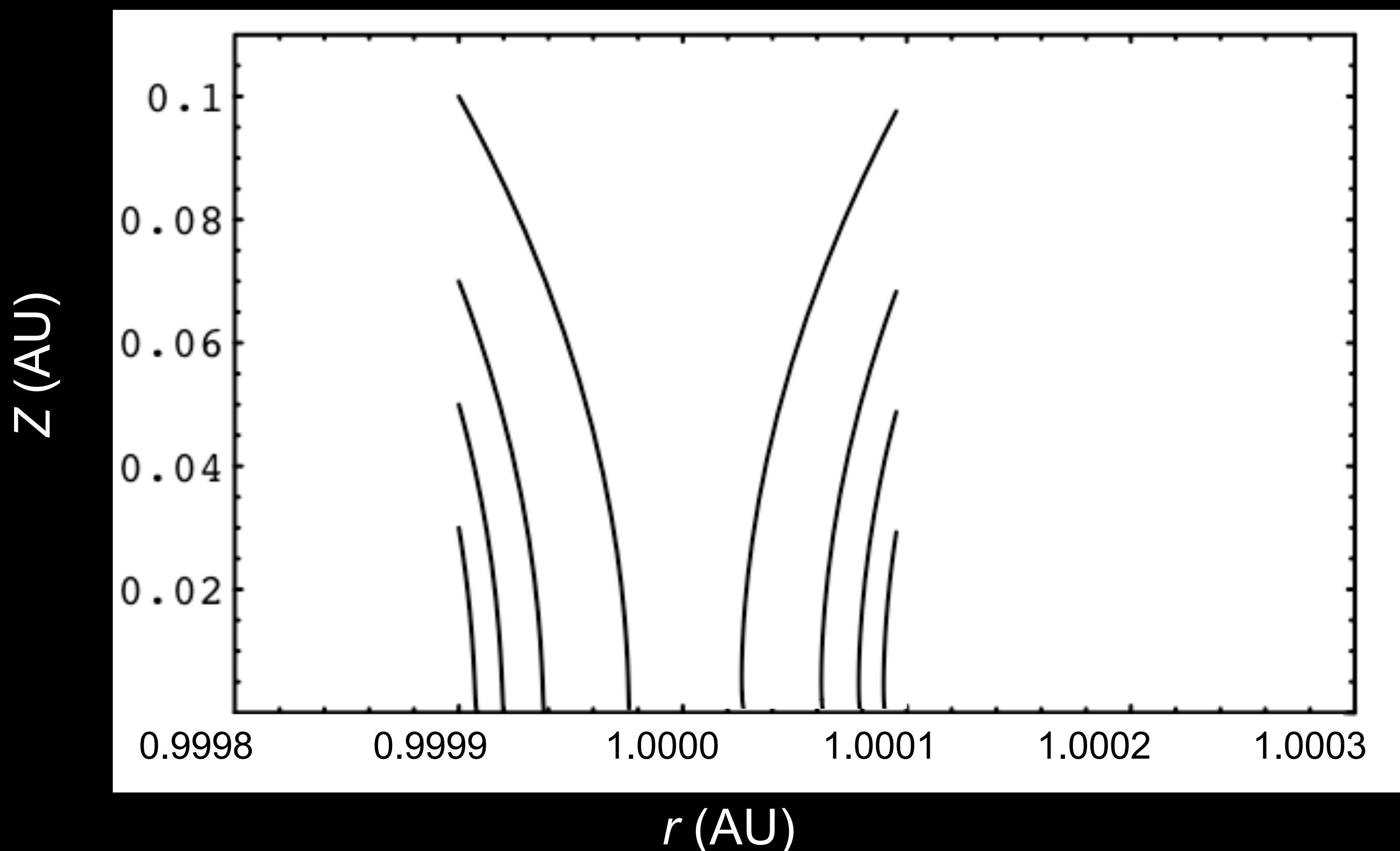
(Haghighipour 2005)

Growth of a 1 micron-sized particle while descending to the midplane





The midplane at *r* = 1 (AU) is populated by mm-sized objects in a few thousand years.



Conclusions

- Combined effect of gas-drag and pressure-gradients causes micron-sized dust particles to migrate towards gas-density enhanced regions while growing to a few millimeter in size.

- The location of the maximum gas pressure/density is turbulence-free since pressure gradients vanish in such locations and the dust and gas rotate at Keplerian velocity.

- Settling dust particles in the location of maximum gas pressure/density form a layer of mm-sized objects which may undergo gravitational instability.

-The appearing and disappearing of gas- density enhanced regions causes the accumulated cm-sized particles to undergo additional migration, and form larger (meter-sized) accumulations.